Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf

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[1] Geophysical data from the Antarctic Peninsula continental shelf reveal streamlined subglacial bedforms in a cross-shelf trough. Bedforms exhibit progressive elongation with distance along the trough, and record flow of a paleo-ice stream from the Antarctic Peninsula Ice Sheet during the last glacial maximum. Downflow evolution of the bedforms indicates increasing flow velocities as the ice stream traversed the shelf. This, in turn, is related to a transition from crystalline bedrock on the inner shelf to a soft sedimentary substrate on the outer shelf. Although streaming flow operated across both substrates, the highest flow velocities occurred over the soft bed. Spatial variation in the inferred nature of fast-flow, from sliding to subglacial sediment deformation and/or ploughing, was also lithologically controlled. These data highlight the control of subglacial geology on ice-stream dynamics in the geological record and demonstrate a direct relationship between the formation of streamlined subglacial bedforms and paleo-ice streams. *INDEX TERMS:* 3025 Marine Geology and Geophysics: Marine seismics (0935); 1827 Hydrology: Glaciology (1863); 9310 Information Related to Geographic Region: Antarctica

1. Introduction

[2] Understanding the future response of the Antarctic Ice Sheet to global climate change necessarily involves investigations of ice-stream dynamics and the processes operating at ice-stream beds. Ice streams, together with fast-flowing outlet glaciers, may account for as much as 90% of drainage from the Antarctic Ice Sheet [*Morgan et al.*, 1982], and they play a key role in controlling its stability and dynamics. Given the relative inaccessibility of the sub-ice stream environment, however, it is increasingly recognised that the paths of paleo-ice streams hold key information about ice-stream processes and their controls [*Stokes and Clark*, 1999; *Shipp et al.*, 1999; *Canals et al.*, 2000]. In Antarctica, identification of zones of former fast flow is critical in order to address questions concerning changes in the stability of the Antarctic Ice Sheet from the Pleistocene to the present day.

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[3] In this paper, we describe streamlined subglacial bedforms that record flow of a paleo-ice stream across the west Antarctic Peninsula continental shelf (Figure 1). The bedforms are located in a trough that extends from Marguerite Bay across the continental shelf to the shelf edge. We address the following questions: (1) what is the paleo-glaciological significance of the streamlined bedforms in terms of the extent of the Antarctic Peninsula Ice Sheet (APIS) along its western margin during the last glacial maximum (LGM)? Previous reconstructions range from an ice sheet that extended to the shelf break [*Pudsey et al.*, 1994] to an ice-sheet restricted to the mid-shelf [*Pope and Anderson*, 1992]. (2) What can we infer about conditions at the former ice-stream bed in regard to the controls on bedform genesis and fast glacier flow?

2. Subglacial Bedforms

[4] EM120 (12 kHz) multibeam swath bathymetry and TOPAS sub-bottom profiler data (0.5–5 kHz) were collected during cruise JR59 of the RRS *James Clark Ross*. The survey extended 400 km across the continental shelf along a trough from inner Marguerite Bay to the shelf edge (Figure 1). Water depths decrease along the trough from about 1600 m on the inner shelf to just over 500 m at the shelf edge. Navigation data were acquired using differential GPS.

[5] On the inner shelf, bedforms at the mouth of George VI Sound comprise short, irregular drumlins and crudely streamlined forms with blunt stoss and more tapered lee sides (Figure 2a). Bedform lengths range from 1100 to 3450 m, while widths range from 300 to 1900 m. Length to width ratios range from 2:1 to 4:1. With distance along the trough, bedforms become progressively more elongate, with lengths of 2830–6830 m, widths of 550–2350 m and length to width ratios of 3:1–9:1 (Figure 2f). The irregular appearance of the seafloor (Figure 2a), and lack of acoustic penetration of the seabed on TOPAS profiles, suggest that sediment cover is thin and localized in the inner shelf trough [cf. *Pope and Anderson*, 1992] and that many of the bedforms are at least partially formed in bedrock. Occasional meltwater channels are present (Figure 2b). Channels show areas of overdeepening along their thalwegs, suggesting they are of subglacial origin.

[6] Across the mid-shelf, bedforms become progressively more elongate (Figures 2d and 2f), and their increasingly smooth appearance on the swath bathymetry suggests a gradual transition to forms composed predominantly of sediment. However, bedrock crops out locally at the surface in this region, suggesting that sediment cover may be relatively thin. Bedform lengths range from 3200–10,100 m and widths range from 200–1260 m. Length to

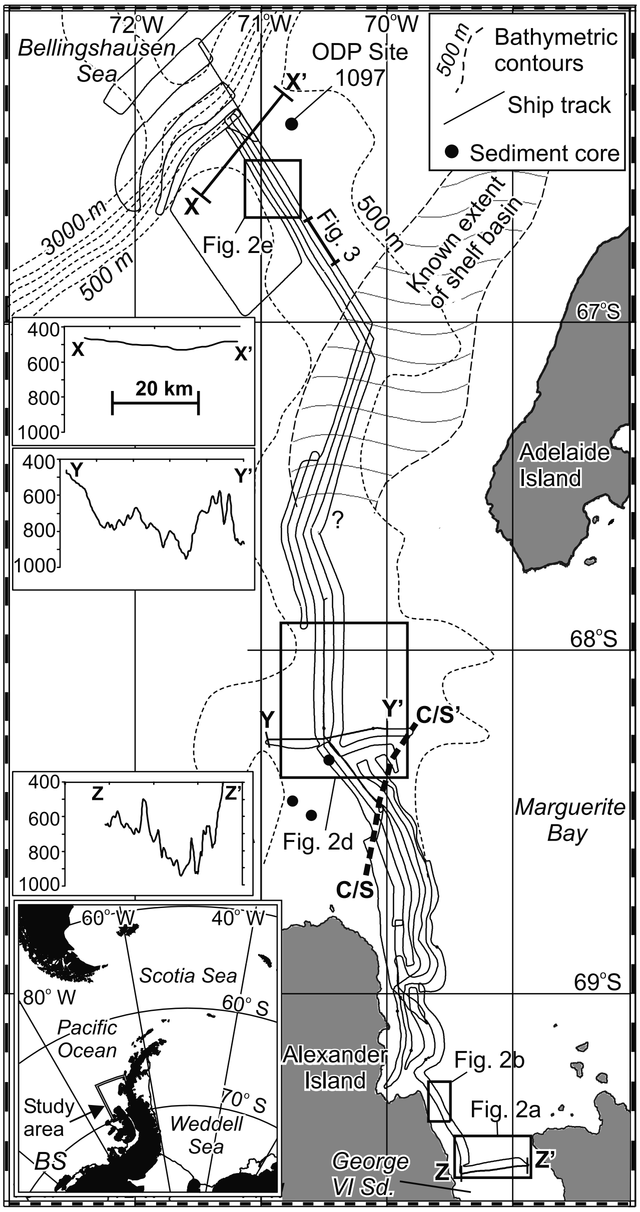

Figure 1. Location map of the study area showing bathymetry, ship track and location of cores containing basal till [*Kennedy and Anderson*, 1989] referred to in text. The cross-shelf trough is defined by the 500 m contour. Bathymetric profiles XX′, YY′ and ZZ′ show the high relief of the trough and the bedforms within it on the inner and middle shelf, compared with the outer shelf. The dashed line CSCS′ demarcates the approximate transition between crystalline bedrock and sedimentary substrate. Outline of sedimentary basin on shelf is from *Larter et al.* [1997]. "BS" on inset map = Bellingshausen Sea.

width ratios range from 4:1 to 31:1, with the majority greater than 7:1. Bedforms comprise classical drumlins, highly attenuated drumlins, and shallow lineations/flutings (Figures 2c and 2f). The stoss-sides of several drumlins exhibit crescentic overdeepenings, and the most attenuated bedforms occur in the deepest parts of the trough (Figure 2d). Subglacial meltwater channels are occasionally present (Figure 2d). Piston cores, up to 4.8 m long, recovered from the trough (Figure 1) penetrated overconsolidated, massive diamicts that are texturally and mineralogically homogeneous [*Kennedy and Anderson*, 1989]. Their composition indicates a restricted source on northern Alexander Island, and *Kennedy and Anderson* [1989] interpret them as basal tills.

[7] Drumlins are replaced on the outer shelf, north of 67°32′S, by mega-scale glacial lineations (MSGL) formed in sediment (Figure 2e). MSGL extend to the shelf edge but become progressively disrupted by iceberg plough marks in water depths of less than 520 m. MSGL are about 10,000 m to >17,000 m long and 130–400 m wide. Length to width ratios increase from about 30:1 to 90:1, falling to 77:1 towards the shelf edge (Figure 2f). TOPAS profiles show a thick (8–15 m), acoustically transparent sediment layer with a smooth basal reflector, overlain by a thin transparent drape (Figure 3). The layer is restricted to the trough and is interpreted as till. Drilling at ODP site 1097 (Figure 1) recovered massive, matrix-supported diamictite with reworked marine microfossils that *Eyles et al.* [2001] interpreted as deformation till.

3. Paleo-Glaciological Significance

[8] Streamlined subglacial bedforms in Marguerite Trough become progressively more elongate from inner Marguerite Bay to the shelf break. This bedform continuum records the former presence of a major, grounded ice stream that drained through Marguerite Trough and reached the continental shelf edge during the LGM. This interpretation is supported by: (1) the bedforms occur in a cross-shelf trough and such troughs are commonly loci for ice streams draining modern ice sheets; (2) downflow evolution in the morphology of subglacial bedforms along the trough (Figure 2f) is consistent with a progressive increase in ice-stream velocity across the shelf [cf. *Clark*, 1993; *Shipp et al.*, 1999]; (3) the most elongate bedforms on the mid-shelf are located in the central part of the trough where flow velocities would be highest; (4) bedform orientation indicates convergent ice flow into the trough; and (5) the restricted source area for basal tills in the mid-shelf trough [*Kennedy and Anderson*, 1989]. Transitions between bedforms are gradational and large-scale switches in flow direction as evidenced by well-developed, spatially extensive, zones of crosscutting bedforms are absent. This is consistent with bedform generation by streaming flow along the length of the trough. Crosscutting, where present, is both localized and relatively minor. The apparent absence of a mid-shelf grounding-zone, well-preserved nature of the bedforms, and absence of large-scale bedform crosscutting, points to rapid deglaciation of the trough.

[9] The ice stream had a maximum length of about 370 km if our interpretation of streaming flow along the length of the trough is correct. The substrate changes from crystalline on the inner shelf, to sedimentary across the mid-outer shelf [*Bart and Anderson*, 1995; *Larter et al.*, 1997]. The gradational continuum of subglacial bedforms suggests that streaming flow operated across both substrates. Estimates of ice-stream width are constrained by our data coverage, but if it is assumed that the ice stream filled the trough as defined by the 500 m bathymetric contour (Figure 1), it would have been about 35 km wide and >400 m thick at the terminus. This thickness estimate is based on ~500 m water depth at the shelf edge minus 120 m eustatic sea level rise since the LGM, but it disregards local glacioisostatic effects. This cross-section would produce an ice flux of 14 km^3 yr^{-1}, assuming a velocity of 1 km yr^{-1}.

4. Conditions at the Ice-Stream Bed

[10] Cores and TOPAS data indicate the presence of basal till in the mid-outer shelf trough. Till formation was probably controlled by the change in substrate from crystalline bedrock on the inner shelf, to sedimentary bedrock across the mid-shelf, to a thick sequence of Cenozoic glacigenic sediments on the outer shelf

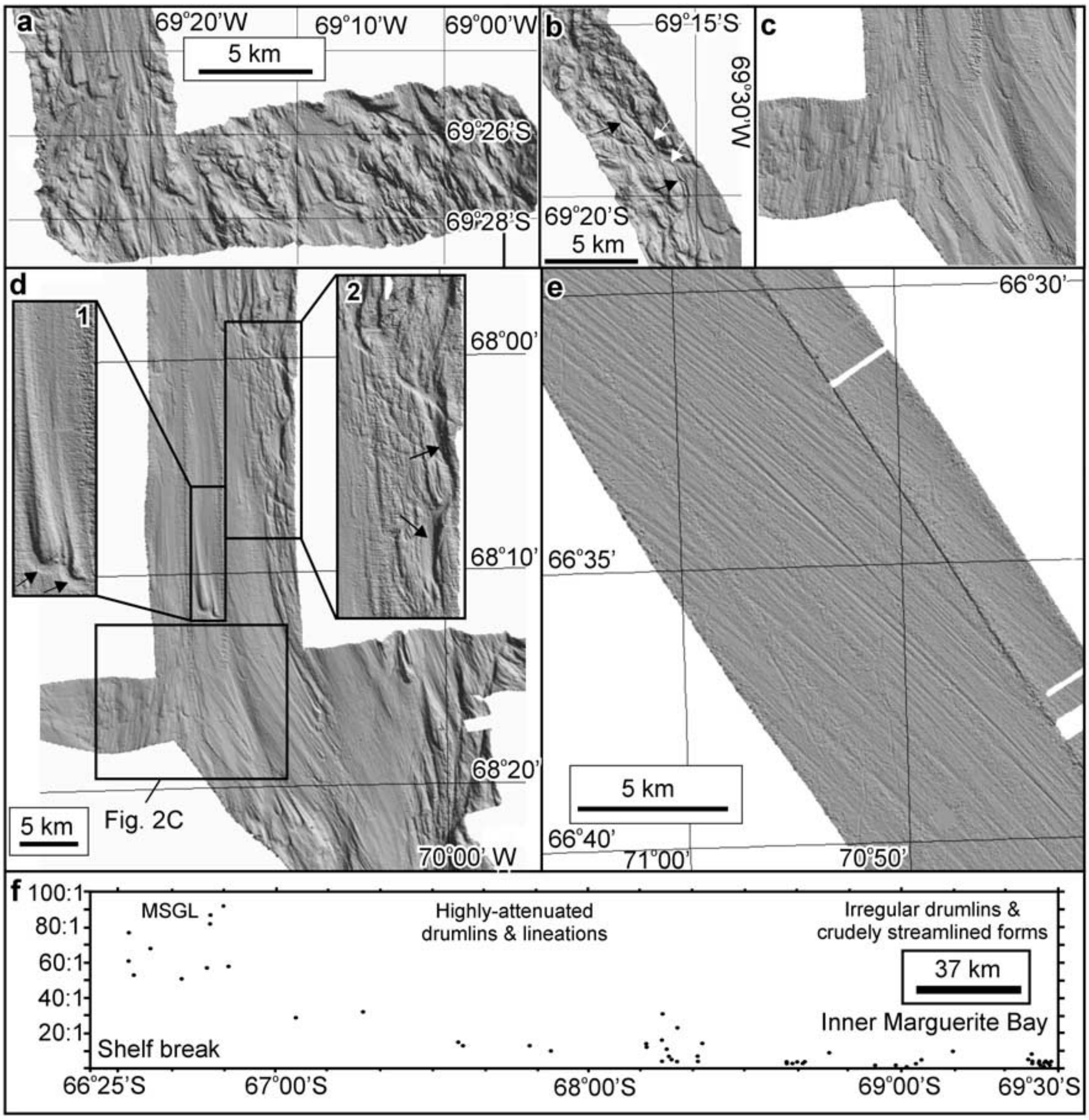

Figure 2. EM120 shaded relief images of streamlined subglacial bedforms in Marguerite Trough. Locations are shown in Figure 1. (a) Short irregular drumlins and crudely streamlined forms, inner Marguerite Bay. Grid cell size = 35 m × 35 m; (b) Meltwater channels in bedrock (arrowed), inner Marguerite Bay. Grid cell size = 35 m × 35 m; (c) Convergence of streamlined bedforms into the deepest part of the trough. Grid cell size = 30 m × 30 m. (d) Drumlins and lineations formed in sediment and bedrock on the middle shelf. Grid cell size = 30 m × 30 m. Inset 1 shows highly-attenuated drumlins with crescentic overdeepenings (arrowed) around their stoss-sides. Maximum height of the drumlins is 120 m. Inset 2 shows a sinuous meltwater channel (arrowed). Maximum depth of the channel is 230 m; (e) Mega-scale glacial lineations (MSGL) on the outer shelf. Maximum height of the lineations is 15 m and widths range from 130–300 m. Grid cell size = 25 m × 25 m; (f) Relationship between length-width ratio of subglacial bedforms (y-axis) and distance northwards along Marguerite Trough (x-axis).

[*Bart and Anderson*, 1995; *Larter et al.*, 1997]. A sedimentary substrate would be inherently more susceptible to subglacial erosion and would have facilitated till development beneath the ice stream which, in turn, would have acted as a lubricant facilitating fast flow [*Anandakrishnan et al.*, 1998; *Studinger et al.*, 2001].

[11] TOPAS data from the outer shelf show a till layer in which MSGL are formed (Figure 3). MSGL record the highest flow velocities [*Clark*, 1993] and indicate ice/bed coupling. Ice/bed separation and sliding are thus unlikely to have been widespread here. This is supported by the absence of meltwater forms on the MSGL, suggesting that meltwater evacuation was largely accommodated through the bed in this region. Fast flow across the soft bed therefore most likely records some combination of subglacial sediment deformation and/or ploughing [*Alley et al.*, 1986; *Tulaczyk et al.*, 2001].

[12] Geophysical data indicate that sediment cover is thin and localized on the inner shelf [cf. *Bart and Anderson*, 1995]. However, streamlined bedforms suggest that fast flow operated in this region also. We interpret this to have resulted from the presence of meltwater at the bed, which would have facilitated decoupling, enhanced basal sliding and rapid glacier motion [*Engelhardt and Kamb*, 1998]. Generation of subglacial meltwater and warm-based conditions would have been promoted by strain heating due to convergent flow into the trough. Evidence for subglacial meltwater is present in the form of subglacial meltwater channels, and crescentic overdeepenings around the stoss sides of drumlins (Figure 2d).

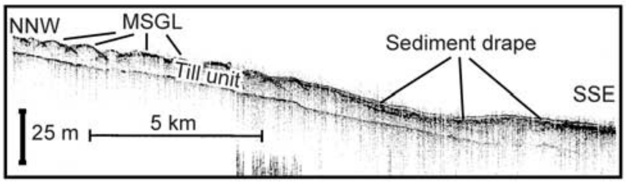

Figure 3. TOPAS sub-bottom profiler record of acoustically transparent sediment layer interpreted as till within the trough on the outer shelf. "MSGL" = Mega-scale glacial lineations.

[13] In conclusion, rapid flow of an ice stream along Marguerite Trough appears to have occurred by a variety of processes including sliding, sediment deformation and/or ploughing, the spatial location of which was coupled strongly to substrate lithology. The gradational continuum in bedform morphology and the intimate relationship with the substrate, such that the most elongate forms are associated with a soft bed, indicates a direct connection between the genesis of streamlined subglacial bedforms, subglacial geology and fast glacier flow in the geological record.

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